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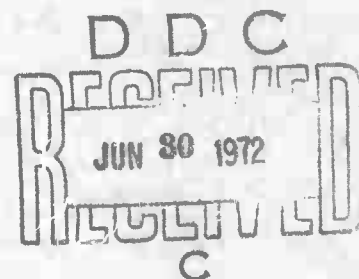
**AIR FORCE CAMBRIDGE RESEARCH LABORATORIES**  
L. G. HANSCOM FIELD, BEDFORD, MASSACHUSETTS

# **Laser Damage Study With Subnanosecond Pulses**

**Technical Report No. 1**

**Period 8 April 1969 to 31 December 1971**

**E.S. BLISS, CAPT, USAF**  
**D. MILAM**



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OPTICAL PHYSICS LABORATORY

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**AIR FORCE CAMBRIDGE RESEARCH LABORATORIES**

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## **Abstract**

**This report describes a ruby laser test facility for conducting laser-induced damage experiments with single subnanosecond pulses. The facility includes a laser damage monitoring system and a mode-locked oscillator-amplifier system with pulse selection.**

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## **Technical Report Summary**

### **Purpose of Project**

The purpose of this research is to gain an understanding of the processes by which laser radiation causes damage to nominally transparent materials, especially those used in the lasers themselves. This particular effort is limited to an investigation of damage caused by subnanosecond pulses and complements both the theoretical studies being done by Capt. Bliss on Air Force funding (Bliss, 1971 and 1972) and the various external research contracts being funded by both the Air Force and ARPA.

### **Equipment Development**

This project began against a background of confusing and contradictory information concerning laser induced damage to transparent dielectrics. Experimental results of different workers were difficult, often impossible, to compare, and the connection between theoretical and experimental results was tenuous at best. Having concluded that lack of appreciation for the complexity of the problem had led to inadequate experimental control and monitoring in earlier work, we undertook the task of designing, building, and testing a ruby laser damage test facility capable of obtaining experimental data under carefully controlled and fully monitored conditions. A detailed description of the facility provides the main subject matter for this report.

## Conclusions

The laser damage test facility developed at Air Force Cambridge Research Laboratories under ARPA Order 1434 is the only facility known to this author capable of performing fully monitored and properly controlled laser damage experiments with single subnanosecond pulses. Results of the first measurements will appear in the next semiannual technical report.

# **Laser Damage Study With Subnanosecond Pulses**

**Technical Report No. 1  
Period 8 April 1969 to 31 December 1971**

## **1. INTRODUCTION**

Damage thresholds under both ruby and glass laser radiation are influenced by a large number of variables (Bliss, 1971). For example, temperature, pulse duration, optical pumping conditions, beam diameter, beam focusing, laser frequency, and details of material growth and preparation all appear to be significant in particular instances of laser damage. This multiplicity of variables often makes it difficult or impossible both to compare various experimental findings with each other and to understand their relation to a particular damage theory or to an operational laser system. Measurements of damage threshold reported in the literature, for example, show considerable scatter. This probably results from significant variations in important parameters from one experimental arrangement to another. Clearly these parameters must be very carefully monitored in order to perform useful experiments. The laser damage monitoring apparatus designed to accomplish this is described in Section 2.

Meaningful laser-induced damage experiments with subnanosecond pulses also require a reproducible mode-locked laser output with excellent beam quality and a means of selecting a single short pulse from the mode-locked train. At the time

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(Received for publication 29 March 1972)

this project began a mode-locked ruby oscillator was operating in our laboratory, but it could not meet the reliability, beam quality, and pulse selection requirements simultaneously. Eventually it became clear that a new oscillator design and a different approach to pulse selection were required. It was also discovered that severe distortion of the beam's circular cross section occurred when the selected pulse was amplified in the ruby amplifiers available. Section 3 of this report describes the present oscillator-amplifier system in which these problems have been largely solved.

A brief description of plans for the initial damage measurements is contained in Section 4.

## 2. LASER DAMAGE MONITORING APPARATUS

The apparatus for monitoring damage experiments on a shot by shot basis is shown in Figure 1. The parameters monitored are the pulse energy, the beam's transverse intensity profile, pulse duration, sample temperature, and sample flash lamp performance. In addition this apparatus has some control capabilities. The incoming pulse energy, the focusing configuration, the beam diameter at the sample, the optical pumping to which the sample is exposed, and the sample temperature can all be independently varied as well as monitored.

Since the way in which these monitoring and control functions are accomplished is a little difficult to see in the complete system diagram of Figure 1, each function will be examined separately in the remainder of this section.

### 2.1 Pulse Energy Measurement and Control

The pulse energy is measured both before and after it passes through the damage sample as shown in Figure 2. The before-sample measurement is made by deflecting 1% of the total energy out of the main beam into an EG&G Model 570 radiometer. The after-sample measurement is made by collecting the entire main beam (except for known losses due to beam splitters and other surfaces) in a Quantronix Model 500/503 calorimeter. The two measurements can be checked regularly for consistency and will also provide a way of measuring any significant amounts of energy scattered or absorbed by a damage event.

The incoming energy can be controlled by varying the concentration of a  $\text{CuSO}_4$  solution at the entrance to the apparatus as shown in Figure 1, which makes it possible to operate the laser source at some optimum output level for each shot. This may be important since the beam profile of laser systems typically changes as the pump level is changed.

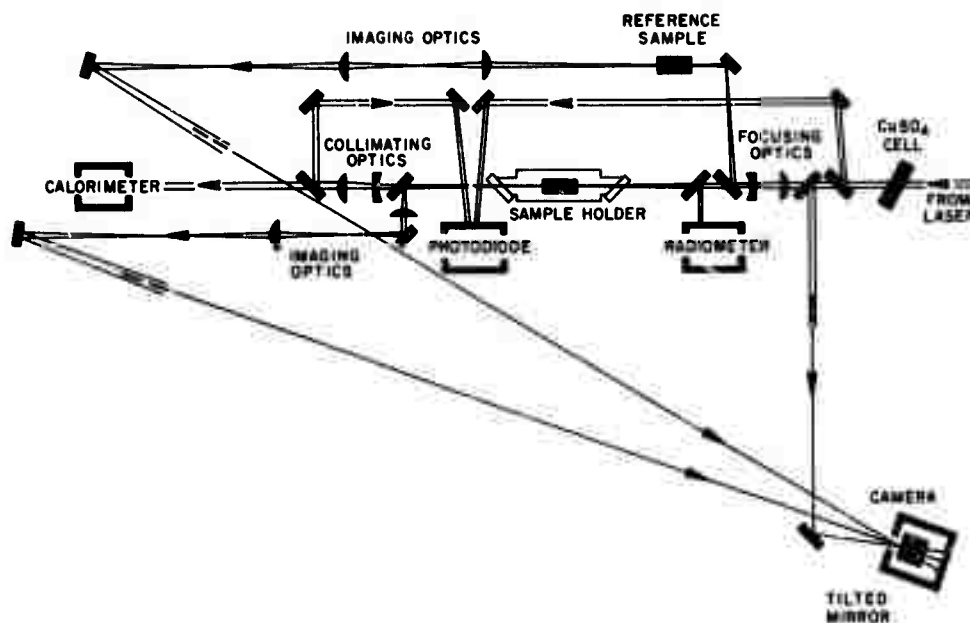


Figure 1. Laser Damage Monitoring System

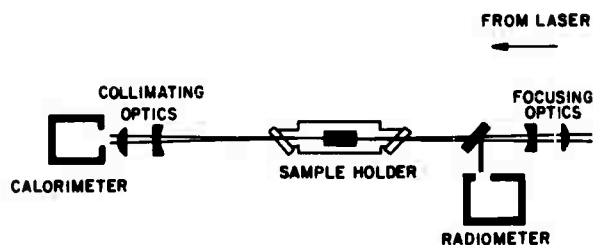


Figure 2. Pulse Energy Measurement

## 2.2 Transverse Intensity Profile Determination

One of the most obvious shortcomings of many early laser damage experiments and some rather recent ones is a lack of knowledge of the intensity variations over the beam cross section. A camera for examining laser outputs by multiple exposure level photography is illustrated in Figure 3. The beam passes through a tilted glass plate with partially reflecting surface coatings. As seen in the figure the beam is split into a series of parallel beams of successively less intensity. The physical separation between adjacent beams is determined by the thickness and angle of the plate, and the decrease in intensity between beams depends on the

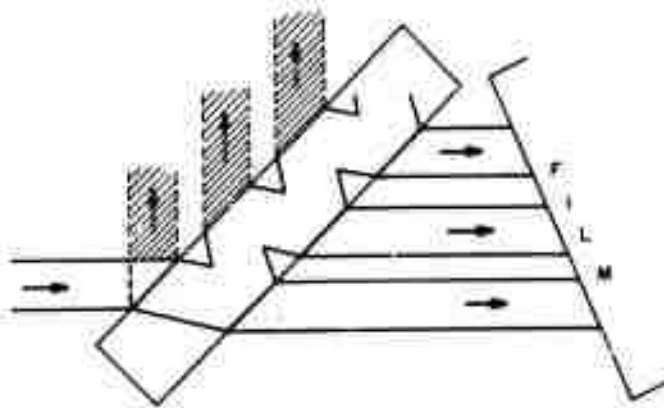


Figure 3. Multiple Exposure Camera Design

reflectivity of the coatings. The film is tilted at an angle such that, when an image is being projected onto the film by an optical system ahead of the glass plate, it will be in focus for all of the beam paths simultaneously.

The capabilities and importance of such a monitoring device are demonstrated in Figure 4. The large intensity variations present in the multimode beam are in striking contrast to the smoothly varying intensity profile of the mode controlled output. When damage experiments are conducted with a multimode beam, an approximate average intensity can be measured, but hot spots with peak intensities considerably in excess of the average will be present, and they are probably responsible for the damage. On the other hand, a complete and accurate intensity versus radius curve can be constructed from the photo of the mode controlled beam, (Winer, 1966) and laser damage thresholds determined with such a beam will be much more meaningful.

This camera has been invaluable during the development of the laser oscillator-amplifier system described in Section 3 as a means of checking mode quality and beam distortion effects. However, it was built primarily for use in the laser damage monitoring apparatus as shown in Figure 5. For each firing of the laser source three multiple exposure level photographs are recorded on a single piece of film. One is a check on the quality of the beam as it enters the focusing optics and the other two are magnified images of any desired plane in the damage sample and reference sample, usually the plane in which the focused beam is a minimum and in which damage is expected to occur.

A variety of important information is obtained using this arrangement. The beam size and intensity profile of each pulse in a damage experiment can be directly measured at the site of the damage, so no calculations based on assumptions about the way in which a given lens focuses a particular laser pulse are necessary. By

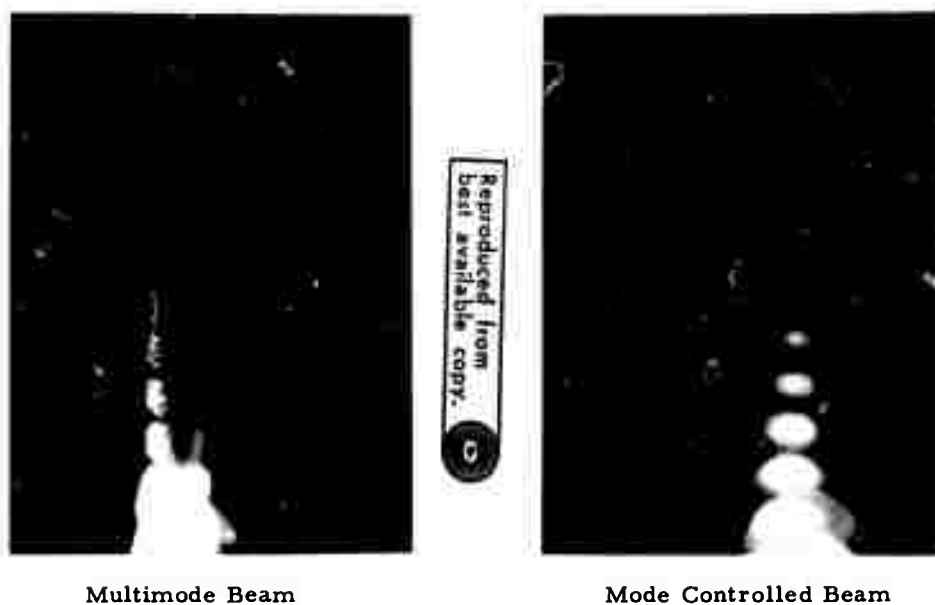


Figure 4. Sample Photos from Multiple Exposure Camera. (Successive exposures differ by a factor of two)

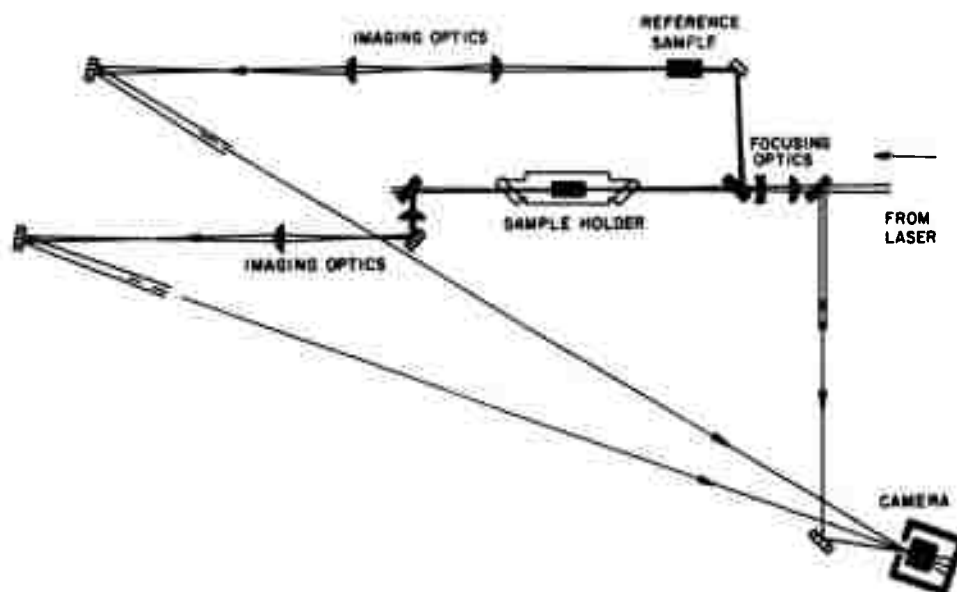


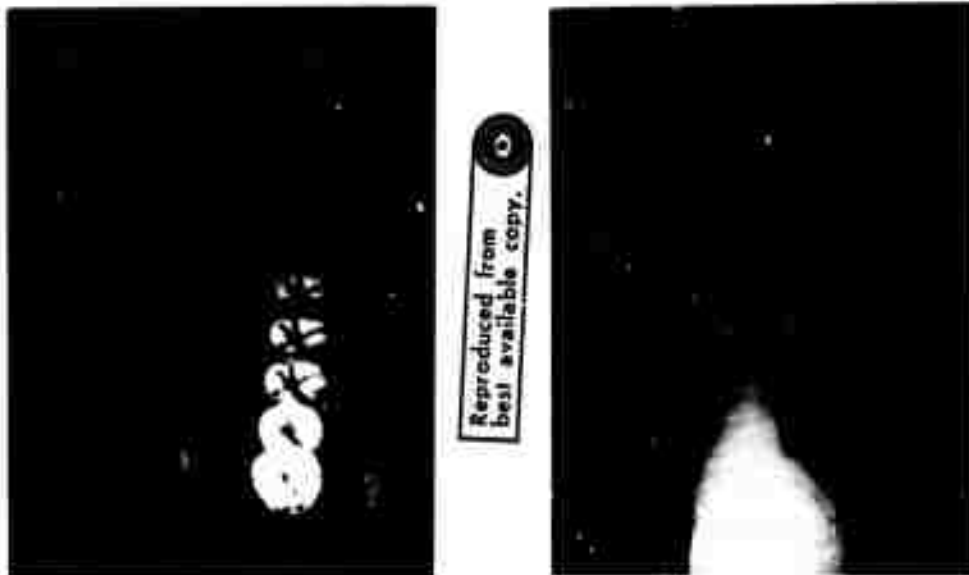
Figure 5. Beam Intensity Profile Measurement



irradiating two samples, a damage sample with the main beam and a reference sample with an identical beam containing only 1% of the input energy, distortion due to self-focusing or scattering from damage sites can be readily identified.

When the laser is operating reproducibly, the transverse intensity profile of the focused beam can be measured as a function of distance along the beam axis by scanning the object planes of the two imaging systems through the samples while taking a series of shots. This particular capability will be useful in conducting experiments for determining the effects of focusing the damaging beam into the sample with varying degrees of sharpness. For such an investigation the effective focal length of the focusing optics can be varied from 25 to 300 cm by changing the interlens spacing. Direct measurement of the resulting beam profile versus axial distance is far more reliable than calculations would be.

When damage is produced, an image of the damage site itself will be produced, either by the light from the damaging pulse or by the next one, depending on whether the visible damage is formed during or after the very short irradiation time. Alternately such an image can be obtained by allowing the gas alignment laser to illuminate the sample as in Figure 6a. Figure 6b illustrates how the variable magnification of the imaging system is determined for a particular setting by placing a reticle in the object plane.



(a) Damage site illuminated by He-Ne alignment laser

(b) Determination of imaging system magnification

Figure 6. Use and Calibration of Damage Imaging System

### 2.3 Pulse Duration Measurement

As seen in Figure 7, 1% of the energy is split off from the main beam both before and after the pulse passes through the sample. The split off beams are directed to a photodiode-oscilloscope detection system with a combined rise time of approximately 0.3 nanoseconds. The additional distance traveled by the part of the beam which is split off after passage through the sample provides enough optical delay to give a two pulse display on a single sweep of the scope. Within the temporal resolution limits of the detector-scope combination, this gives a measure of the pulse duration both before and after the pulse interacts with the sample. Of course, for the mode-locked ruby system being used, this measurement is invariably detection limited. Nevertheless it is still useful for verifying that a well selected, single pulse has been generated and for an instant qualitative indication when energy has been lost in the sample.

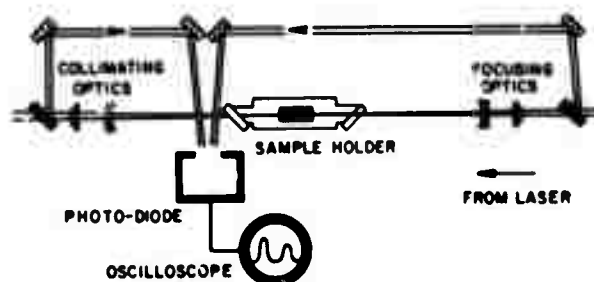


Figure 7. Pulse Duration Measurement

A two-photon fluorescence camera is used for making quantitative measurements of the actual several-picosecond pulse duration. The results of such measurements are used with full recognition of the inherent ambiguities of the intensity correlation process (Picard, et al, 1970). A picosecond resolution streak camera would be preferable, but such an instrument is not yet available to us.

### 2.4 Miscellaneous Features

A variety of sample holders is available. For most experiments the samples will be mounted on a simple V-block which can be translated along the beam and across the beam, both vertically and horizontally. In some cases, however, it may be desirable to measure laser damage events as a function of temperature and optical pumping level. For such experiments a small laser oscillator head with Brewster angle windows and liquid nitrogen cooling is available as a sample holder.

In this arrangement the temperature is measured by a copper-constantan thermocouple and the relative pumping level is monitored with a light pipe and photomultiplier.

### 3. LASER OSCILLATOR-AMPLIFIER SYSTEM

Conducting damage experiments with a single subnanosecond pulse requires a laser source consisting of a mode-locked oscillator, a pulse selector for removing a single pulse from the train, and an amplifier chain for increasing the pulse energy to a usable level. Each of these components is described below.

#### 3.1 TEM<sub>00</sub> Mode-Locked Oscillator

Conventional mode-locked ruby lasers, constructed in accordance with guidelines published to date, are generally not suited for use as a quantitative laboratory tool. At best, the probability of obtaining a cleanly locked pulse train with a ruby laser that is passively mode-locked is approximately 0.6 to 0.7 when the laser is operating at its highest level of performance (Mack, 1970). The rest of the time the output contains more than one pulse per time period of  $2L/c$  (where  $L$  is the length of the laser and  $c$  is the speed of light). The multitransverse-mode intra-cavity power density is so large that component damage frequently occurs, and as discussed in Section 2.2, a multimode output is not useful for meaningful measurements of damage. Attempts at TEM<sub>00</sub>-mode operation with large-diameter ruby rods require the use of an aperture to reduce the Fresnel number of the cavity to about unity, but we have found that introducing an aperture disrupts the mode-locking because of scattering from the edges of the aperture.

To obtain transverse mode control and at the same time generate cleanly mode-locked pulse trains a unique ruby oscillator has been designed and built in-house (Milam et al, 1971). The new feature of the design is the use of a rod only 2.5 mm in diameter so that the rod itself is the limiting aperture of the system. The smooth transverse intensity profile which results reduces the maximum power density in the cavity, and shortening the rod length to 76 mm further reduces the power so that mirror damage is not a problem.

The cavity is comprised of the ruby rod, a wedged 40-percent output mirror, and a combination mirror and dye cell which uses a 95-percent mirror in place of one of the dye cell windows (Bradley et al, 1970a). The wet-mirror dye cell is shown in Figure 8. It is known that a thin dye layer is preferable for mode-locking (Bradley et al, 1970b). The construction of a thin cell from which the dye is easily flushed is simplified by using a lipped, wedged window. All parts required

for the cell are large and easily machinable from substances that will not contaminate the dye solutions. A large syringe serves as a dye reservoir. The syringe is connected to the cell by long flexible sections of hypodermic needle stock so that the cell can be filled or flushed without disturbing the cavity alignment.

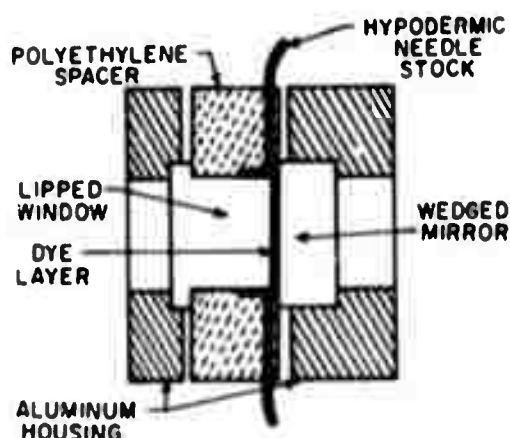


Figure 8. Wet Mirror Dye Cell

Solutions of 1,1'-diethyl-2, 2' dicarbocyanine iodide (DDI) in methanol, or cryptocyanine in acetone, with small-signal transmissions of 60 percent to 75 percent for the 0.25-mm to 0.50-mm dye cell thickness are used to simultaneously Q-switch and mode-lock the laser. The cell is flushed after each shot so as to minimize effects due to dye degradation.

The ruby rod is placed near the center of an approximately one meter long cavity as shown in Figure 9. It is excited with a helical xenon flash lamp surrounded by a powdered MgO diffuse reflector. The ruby and lamp are cooled by flowing water and forced air respectively. A typical pulse train and time-integrated multiple exposure of the transverse mode pattern are shown in Figure 10.

Since the pulses are too short to be resolved even on the fastest diode and oscilloscope combination, their duration has been estimated from time-integrated two-photon fluorescence photographs recorded by means of the standard triangular mirror arrangement and rhodamine 6G (Giordmaine et al, 1967). The entire width of the recorded enhanced exposures corresponds to about 45 picoseconds. Although deducing an exact pulse duration from the intensity autocorrelation function depends on knowledge of the pulse shape and a measurement of the contrast ratio (Picard et al, 1970), a reasonable estimate of the pulse width is 20 to 25 picoseconds. The pulse duration measured by this technique is reduced to approximately 10 psec by incorporating a telescope in the cavity

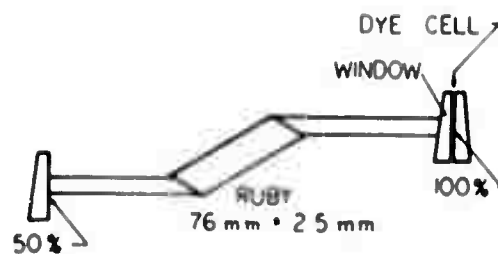


Figure 9. Oscillator Cavity

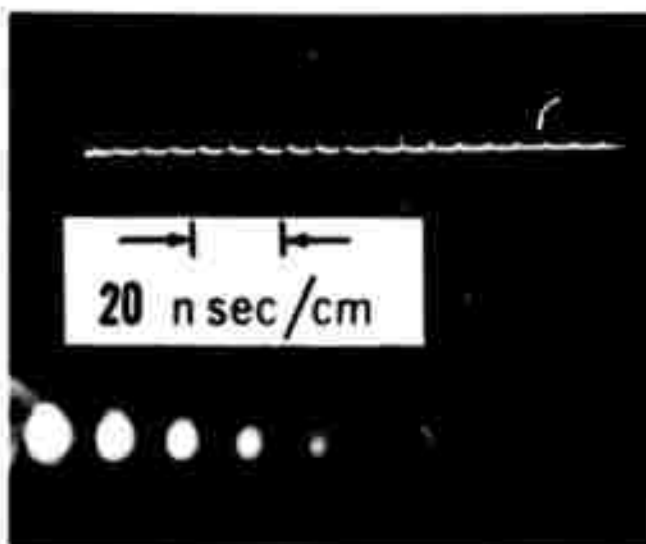


Figure 10. Oscillator Output

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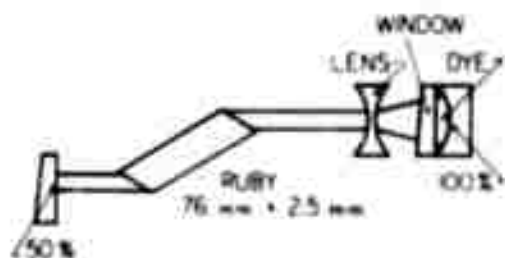


Figure 11. Oscillator Cavity with Telescope

as shown in Figure 11. The improvement is probably due to the fact that reflections off of the cell window now diverge as they return toward the rod and hence can not contribute to a buildup of energy in the wings of the initial pulse.

To check for the possibility that the pulse duration changes during amplification or that pulses from different parts of the train have different durations, two-photon measurements of single amplified pulses are planned.

This oscillator produces cleanly locked pulse trains more than 80% of the time. The energy of the total train is  $3 \pm 0.5$  mJ with the energy of individual pulses varying by  $\pm 50\%$ .

### 3.2 Selection of a Single Mode-Locked Pulse

Removal of a single pulse from the mode-locked train is accomplished by placing a Pockel's cell between crossed polarizers in the output beam of the laser. The Pockel's cell is driven to half-wave voltage by a laser-triggered spark gap. The polarization of any pulse passing through the Pockel's cell while the voltage is being applied is rotated by  $90^\circ$  and that pulse is transmitted by the second polarizer. In order to reliably select a single pulse on each firing of the laser, the Pockel's cell must either be held at voltage for a large fraction of the pulse separation time (about 7 nsec for the oscillator described in Section 3.1) or the spark gap must be fired with sufficiently low jitter that a shorter voltage signal can be applied to the Pockel's cell in synchronism with the arrival of a locked pulse. Our first effort at building a pulse selector took the latter approach.

Several articles recently published by Guenther et al\* furnish a strong technical basis for the construction of low-jitter laser-triggered spark gaps. Various design considerations such as electrode material and spacing, type and pressure of the gas fill (Bettis and Guenther, 1970), polarity and magnitude of the voltage across the gap, and power levels and focal conditions of the laser beam used to trigger the gap have been investigated in detail (Guenther and Bettis, 1967b). Reliable switching with subnanosecond jitter has been reported (Bettis and Guenther, 1970) when a single-mode, Q-switched Nd - YAG laser is used. Such a laser is ideally suited for switching spark gaps for several reasons: (1) the smooth time profile of the pulse causes the plasma production in the gap to be a continuous, slowly varying process; (2) the TEM<sub>00</sub>-mode guarantees that the focal conditions remain constant from shot to shot; and (3) the power level required to produce breakdown is relatively low for the Nd - YAG wavelength.

Unfortunately, a mode-locked laser is not an ideal source for switching spark gaps. The energy contained in the pulse train arrives at the spark gap in the form of short pulses separated by time intervals which may be long compared to gap breakdown times. Plasma produced by a given picosecond pulse decays from the

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\* (1967a, 1967b, 1970) and Bettis and Guenther (1970).

focal volume due to diffusion and recombination. At the same time the plasma density may increase as a result of inverse bremsstrahlung under the influence of the field applied across the gap. If the degree of ionization produced by a given picosecond pulse is insufficient to lead to avalanche during the interval between pulses, an additional quantity of ionization is supplied by the next pulse and the loss and gain processes begin anew from some higher initial state of ionization. This can be a low jitter process only if the laser generates exactly reproducible mode-locked pulse trains, which is not the case. The best one can hope for is that the gap will fire with low jitter relative to some pulse in the train even though the jitter relative to the envelope of the train may be large.

For our purposes the spark gap must not only fire with as little jitter as possible; it must also be impedance matched to the Pockel's cell. We have designed and built an impedance matched device patterned closely after one (von der Linde, et al, 1970) of several described in the literature.\* A cross section of this gap is shown in Figure 12. The 6-mm diameter stainless steel pole pieces are attached directly to UG-560/U coaxial cable connectors which have been altered so as to be gas tight. The gap spacing is maintained by a set of fixed length washers which are changed as necessary to vary the gap spacing in 0.5-mm steps. The laser beam is focused into the gas between the pole pieces by a lens with a focal length of 8 mm and escapes from the chamber through a window. A second window allows observation of the breakdown. A static argon-nitrogen mixture at 5 atmospheres of pressure is maintained in the gap. The gas mixture is adjusted to give self-breakdown at 12 to 13 kilovolts, which is sufficient for production of a half-wave voltage pulse at the KDP Pockel's cell. Different values of self-breakdown, up to about 20 kV, can be obtained by varying the gas composition and pressure.

Figure 13 shows the experimental arrangement used to measure the firing jitter of this gap when it is triggered by our TEM<sub>00</sub>-mode, mode-locked ruby oscillator. The beam is reduced in intensity by 50% and then focused into the gap. When the gas is triggered, energy stored on a section of RG-5A/U cable is discharged into a similar section of cable which is terminated by a 50-ohm load. Signals from a fast planar diode monitoring the laser output and from the pickup which registers the firing of the gap are combined and displayed on a Tektronic 519 oscilloscope. Examples of the data obtained are shown in Figure 14. In (a) the pickup from the gap has been disconnected to obtain a better impedance match between the planar diode and the oscilloscope. Figure 14(b) shows the signal when the gap fires with the pickup loop connected.

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\* (von der Linde et al, 1970; Alcock et al, 1970; Deutsch, 1968; Bradley et al, 1969; Michon et al, 1969).

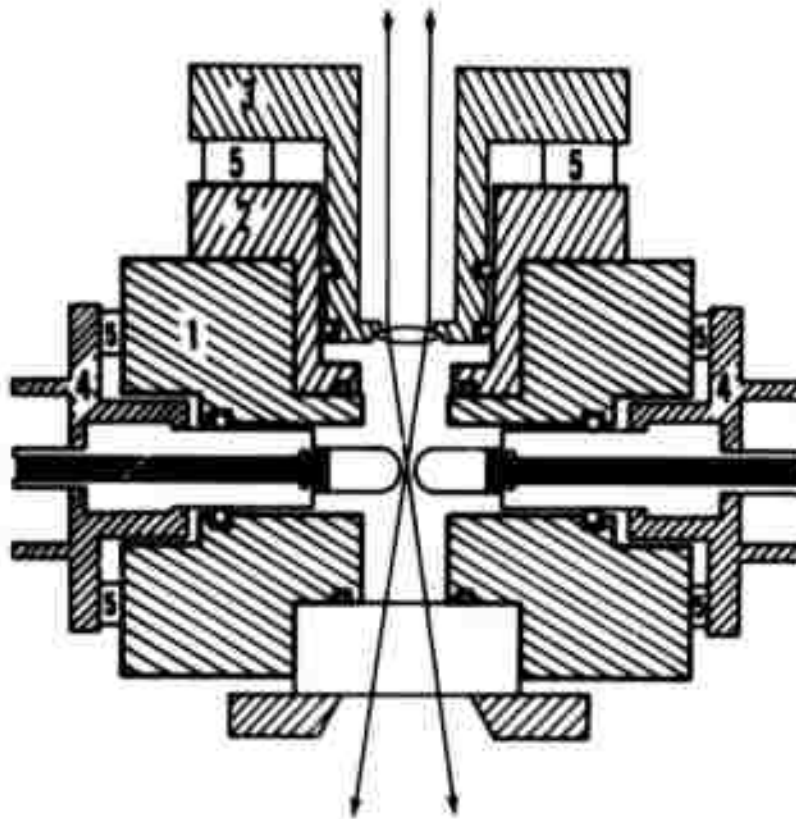


Figure 12. Laser-Triggered Spark Gap

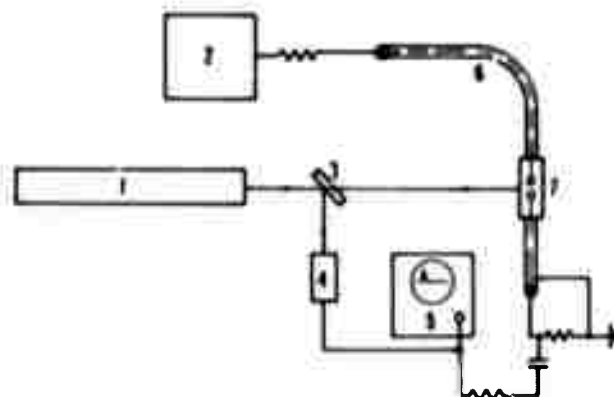


Figure 13. Schematic of Jitter Measurement Apparatus



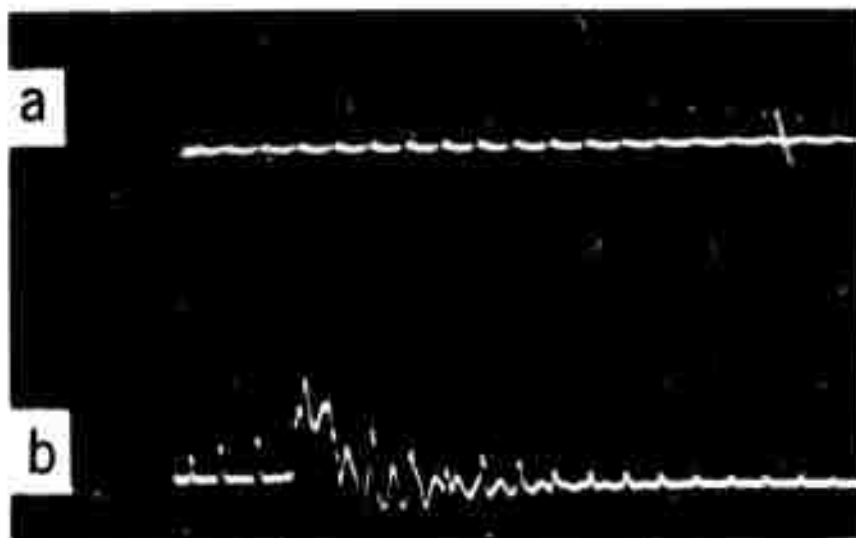


Figure 14. Sample Jitter Data

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Jitter has been measured as a function of lens position with fixed gap conditions, and as a function of the ratio between the voltage on the gap  $V_{\text{gap}}$  and static breakdown voltage  $V_{\text{gb}}$ . The parameter actually measured is the total time delay between the first mode-locked pulse displayed on the oscilloscope trace and the firing of the gap. Delays less than 30 nanoseconds can be determined to within  $\pm 0.2$  nanoseconds. Repeating this measurement a number of times for a given spark gap situation produces a set of turn-on times exhibiting a distribution in time.

If conditions are such that the gap is fired in the early portion of the pulse train, the turn-on times appear in clusters separated by the time between pulses. The clusters can be superimposed by translating each one by an appropriate integral number of pulse separation times. One half the time interval containing 90% of the points in the superimposed clusters is taken as the jitter. Of course, this procedure only determines how closely the firings are associated with the arrival of individual pulses at the gap. It ignores the larger jitter relative to the pulse train envelope. But for such purposes as gating a pulse out of the mode-locked pulse train, the jitter determined by superimposing clusters is the relevant value since it is generally true that any of several pulses occurring in a given portion of the train is acceptable. In any case, it is rarely necessary to move data points by more than one pulse spacing.

When conditions are such that the gap is triggered later in the pulse train, the turn-on times no longer occur in clusters. In these cases it is no longer possible

to clearly identify those firings associated with a given mode-locked pulse, and half the time interval containing 90% of the points in this more smoothly varying distribution is taken as the jitter.

The dependence of jitter on the position of the lens used to focus the beam into the gap is shown in Figure 15 for the case of a 1-mm gap spacing and a five atmosphere, static, argon-nitrogen mixture chosen to produce self-firing of the gap at 12 kilovolts. The initial position of the lens is chosen to focus the laser beam on the axis midway between the pole pieces. The lens is an inexpensive one and no effort has been made to verify the stated 8-mm focal length, but placing the lens 8 mm from the spark gap axis results in the least jitter value. Moving the lens away from the axis of the spark gap increases both the total delay before firing and the jitter. Significant error in lens placement is readily detected by observing the breakdown visually. When the focal region is 2 to 3 mm away from the axis, the breakdown is distinctly curved, whereas optimum lens placement results in a straight, on-axis breakdown.

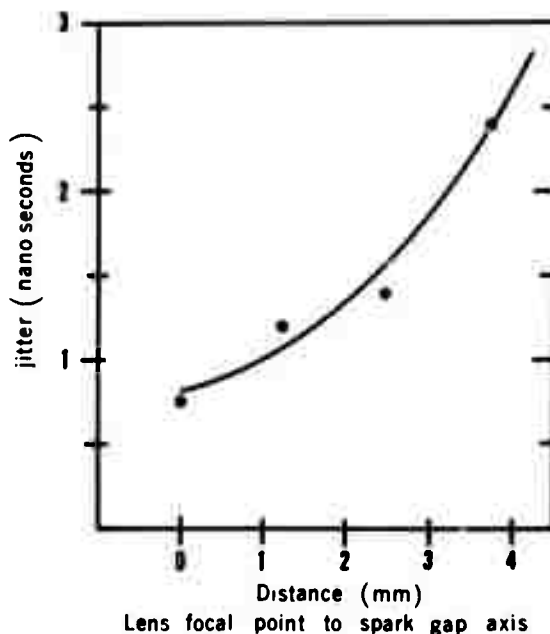


Figure 15. Jitter as a Function of Lens Position

Figure 16 gives typical plots of the firing delay and jitter as a function of the ratio  $V_{\text{gap}}/V_{\text{sb}}$  for the same spark gap conditions. Representative examples of the data obtained for small values of the ratio are shown in Figure 17. It is

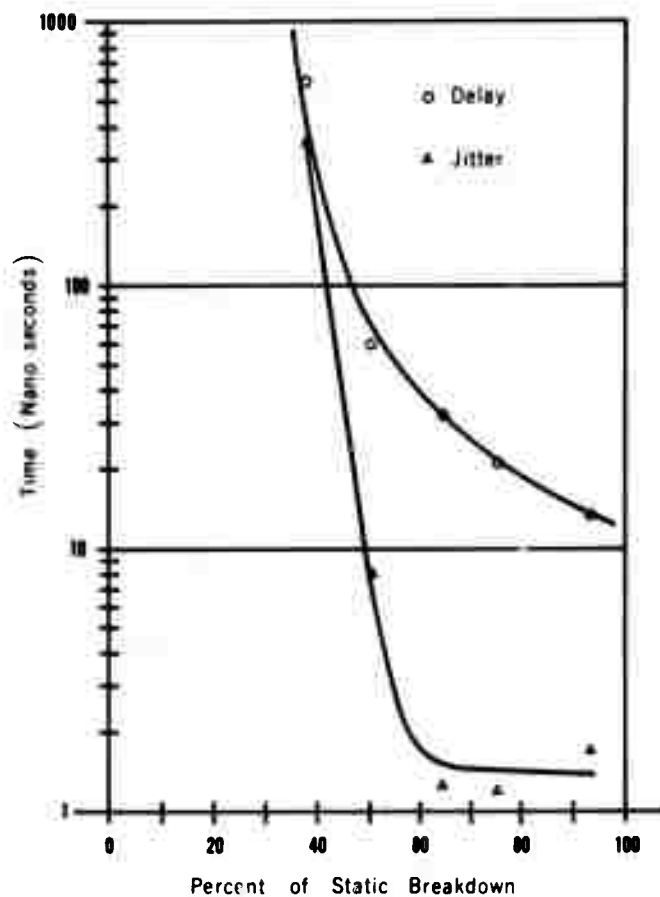


Figure 16. Jitter and Delay as a Function of Voltage

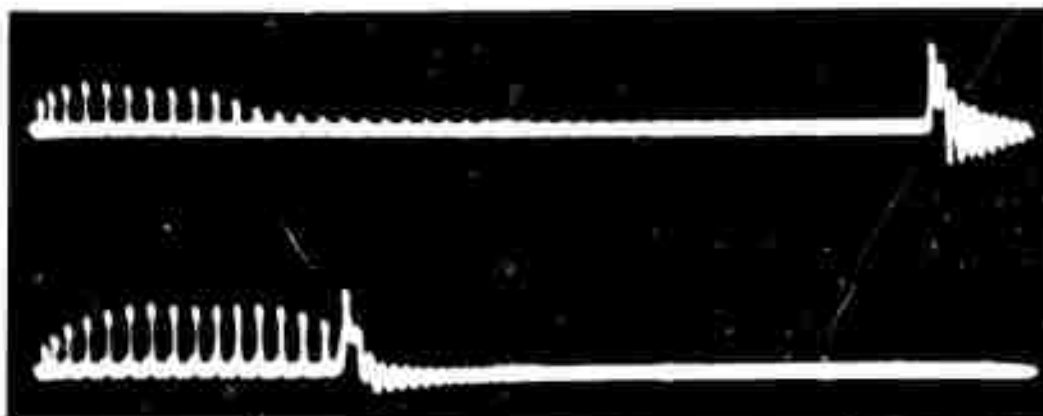


Figure 17. Examples of Low Voltage Jitter Data

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interesting to note that for small values of  $V_{\text{gap}}/V_{\text{sb}}$ , the gap may fire tens of nanoseconds after the principal portion of the pulse has arrived at the gap, indicating that the ionization is integrated during the pulse train.

It may be concluded that when switching is accomplished early in the pulse train it is possible to synchronize the firing of the laser triggered spark with the arrival of individual mode-locked pulses to less than 2 nanoseconds, with an additional jitter of  $\pm$  one cavity round trip time relative to the pulse train envelope. Whereas if the gap is fired late in the pulse train, synchronization with individual mode-locked pulses is lost and the overall jitter may be many cavity round trip times. These observations are consistent with a spark gap model in which the ionization decays from the focal region of the lens with a time constant long compared to the 7 nanosecond interval between pulses, so that ionization may be integrated over several pulses. If avalanche conditions in the gap are achieved with the first few pulses of the train, the switching is closely correlated with the arrival of individual mode-locked pulses since each pulse contributes a large portion of the necessary integrated ionization. By the same reasoning, firings occurring late in the pulse train are poorly correlated with pulse arrival due to the small contribution of each pulse to the ionization.

When properly adjusted and used with the TEM<sub>00</sub> mode-locked oscillator described in Section 3.1, this spark gap triggered pulse selector switches over 90% of a single pulse out of the train approximately half the time. Figure 18 shows a mode-locked train with the selected pulse missing. The rest of the time it selects between 50% and 90% of a single pulse. These departures from ideal switching result from the fact that the gate is not flat topped and the approximately 2 nsec jitter in firing time makes it impossible to center the gate on a pulse on every shot. An improved spark gap - Pockel's cell combination with a longer and flatter gate is presently being tested and will be described in the next semiannual technical report.

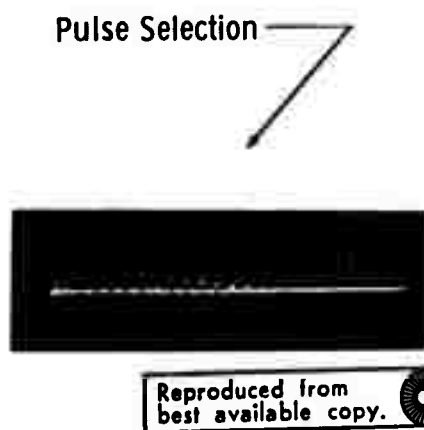


Figure 18. Pulse Selection From a Mode-Locked Train

### 3.3 Amplifier Chain

After producing a clean mode-locked train with the required transverse mode properties and selecting a single pulse from the train, the final step in obtaining an output usable for laser induced damage experiments is to amplify the pulse, preferably to an energy of one tenth of a Joule or more.

All of the amplifiers initially available for this purpose are pumped by two linear flashlamps in a double elliptical cavity. They have been found to distort the beam cross-section severely unless special care is taken. This is apparently explained by the fact that in these cavities the amplifier rods are nonuniformly pumped and heated resulting not only in nonuniform amplification but also in a thermally induced focusing which is not cylindrically symmetric.

Distortion effects can be minimized, but not eliminated, by accurately centering the beam on the amplifier rod axis, using as small a beam as possible consistent with avoiding damaging intensities in the rod, and rotating adjacent amplifiers by  $90^\circ$  about the beam axis so that their asymmetries tend to cancel. A reasonably well amplified pulse and a badly distorted one are shown in Figure 19 along with a pulse selected from the oscillator output.

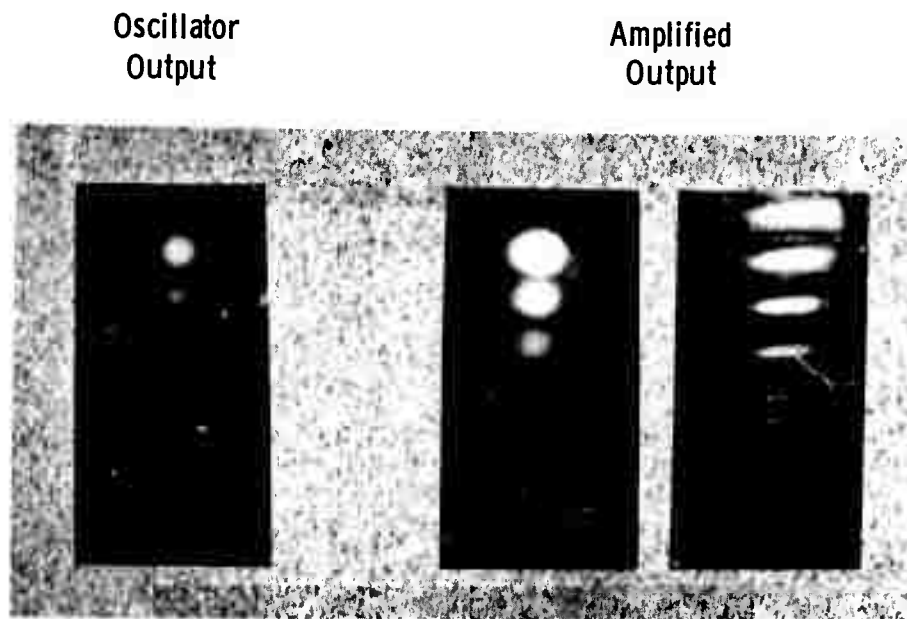


Figure 19. Beam Distortion

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With the hope of eliminating this problem altogether, two amplifiers pumped by helical flashlamps have been ordered, and they should be installed in the system by the end of the next reporting period. Until then the system is being operated with two linear lamp amplifiers and produces slightly distorted pulses with energies up to 40 mJ.

#### 4. PLANNED DAMAGE MEASUREMENTS

During the next reporting period the damage monitoring apparatus and the laser system described in Sections 2 and 3 will be used to make initial measurements of the energy density (energy per unit area) at which ruby, sapphire, and possibly other transparent dielectrics undergo catastrophic damage when irradiated by single ruby laser pulses with a duration of approximately  $10^{-11}$  seconds. These experiments will be followed as soon as possible by further measurements of damage phenomena as a function of beam diameter, beam convergence or divergence, and sample length.

The experimentally determined damage thresholds and their dependence on important parameters will be compared with measurements made with longer pulses at Hughes Research Laboratory and with recent theoretical predictions. The results will aid in the design of lasers which are both more efficient and more reliable.

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